

Estimation of Knee Ligament Injury Measures for a Pedestrian Dummy

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ABSTRACT

In order to enhance understanding of pedestrian injury mechanisms, full-body pedestrian dummies have been developed in past studies. The goal of this study was to estimate knee ligament injury measures for a pedestrian dummy based on the correlation between dummy and human responses. For estimating knee ligament force of the dummy approximating the average ligament failure, finite element (FE) human and dummy knee joint models were subjected to dynamic 4-point bending. The estimated measures for the modified dummy knee ligaments were 3.0, 0.5 and 1.1 kN for the MCL, PCL and ACL, respectively. A full-body FE dummy model was subjected to impacts from a small sedan and a Sport Utility Vehicle (SUV) for validating the estimated force levels. The results showed that the estimated dummy knee ligament force levels predicted failure of human knee ligaments that is likely to take place first when leg fractures are not present in impacts from a small sedan and a SUV.

INTRODUCTION

Accident statistics from the OECD database show that pedestrian fatalities account for a large percentage of all fatalities in traffic accidents in many countries [1]. In particular, they account for more than 30% of all traffic fatalities in Asian countries such as Korea and Japan. In addition, despite a significant decreasing trend in the number of traffic fatalities identified in a Japanese accident database, the number of casualties is still proportional to the number of accidents and is not necessarily in a pronounced decrease [2]. In terms of pedestrian casualties, Kikuchi et al. [3] showed that head and lower limb (including the pelvis) injuries are predominant in Abbreviated Injury Scale (AIS) 2+

pedestrian injuries in both Japanese (Institute for Traffic Accident Research and Data Analysis; ITARDA) and US (Pedestrian Crash Data Study; PCDS) databases. Based on the analysis of AIS 2+ pelvis and lower limb pedestrian injuries in the PCDS database, they also showed that leg fractures and knee injuries dominate for impacts with sedans, while the frequency of pelvis and thigh fractures is relatively higher for impacts with SUVs or mini-vans. This suggests that a tool for investigating mechanisms of injuries to the pelvis, thigh, knee and leg of a pedestrian need to be developed in order to enhance understanding of pedestrian interaction with various vehicles.

In order to reproduce whole-body kinematics of a pedestrian and provide biofidelic response of the knee joint and leg for facilitating investigation of pedestrian head, knee and leg injury mechanisms, a full-body pedestrian dummy called the POLAR II has been developed [4]. In addition, the pelvis and lower limb of the dummy have been further modified for enhanced biofidelity to allow investigation of pedestrian accidents with various types of vehicles [1][5]-[6]. The modified dummy incorporates a flexible structure for the pelvis, thigh and leg to represent compliance of those in a human body. In addition, the knee joint of the dummy includes four knee ligament cables representing major knee ligaments in a human knee joint. In a past study, the authors estimated tentative injury measures for the thigh and leg of the dummy based on the response correlation between full-body FE dummy and human models [1]. However, injury measures for the knee ligaments of the dummy still needed to be estimated.

The goal of this study was to estimate injury measures for the knee ligaments of the modified pedestrian dummy based on the correlation between dummy and

human responses. The knee joint of the dummy is instrumented with four load cells that measure tensile force exerted on an individual knee ligament. For estimating dummy knee ligament forces that approximate the average ligament failure, FE dummy and human knee joint models were subjected to dynamic 4-point bending. For validating the measures, a full-body FE dummy model was subjected to impacts from a passenger car and a SUV. The predicted knee ligament forces normalized by the measures were compared with the knee ligament failure observed in published car-pedestrian impact tests using human subjects and similar types of vehicles.

ESTIMATION OF INJURY MEASURES FOR DUMMY KNEE LIGAMENTS

One way to estimate injury measures for the dummy knee ligaments is to convert experimentally determined human tolerance values for a certain probability of injury to dummy measures by performing similar experiments using the dummy knee joint and correlating human and dummy responses. In case of the knee ligaments, however, human tolerance values determined experimentally using isolated human knee joints are available only for the MCL [9]. Since a FE human knee joint model with the ligaments individually validated against tensile experiments up to failure is available, it was decided to estimate knee ligament failure measures for the dummy based on the correlation in knee bending between the human and dummy models.

DUMMY KNEE JOINT

The knee joint of the original POLAR II dummy incorporates four ligament cables representing human knee ligaments. The tensile properties of the ligaments are provided by ligament springs installed in the spring housing on the femur side of the knee joint. The meniscus made of hard urethane provides biofidelic boundary conditions at the knee joint [7]. Takahashi et al. [8] validated the biofidelity of the knee joint in dynamic 4-point valgus bending against the human response corridor developed by Ivarsson et al. [9]. Since the thigh of the POLAR II dummy consists of a rigid structure, the femur shaft was replaced by a compliant shaft made of polyoxymethylene (POM) for enhancing biofidelity. The same material was also used for the tibia. In order to accommodate longer flexible shafts of the femur and tibia, the vertical dimension of the knee joint was minimized, while the basic design of the knee joint was maintained [1]. Figure 1 illustrates the modifications to the lower limb of the original POLAR II dummy. The biofidelity of the modified knee joint was validated by Bose et al. [10] in dynamic 4-point valgus bending against the human response corridor developed by Ivarsson et al. used for the validation of the original version, showing good biofidelity of the modified knee joint. Figure 2 shows the comparison of the bending

moment at the knee joint as a function of the knee bending angle between the modified knee joint and the human response corridor.

FE DUMMY KNEE JOINT MODEL

A FE model for the dummy knee joint developed by Takahashi et al. [1] was used in the current study (Figure 3). The meniscus was modeled using solid elements to represent its compliance. For simplicity, only the portions of the knee ligament cables exposed from the distal femur or proximal tibia were represented by bar elements, without modeling the ligament cables inside the knee joint structure. The mass of the ligament springs and cables was lumped into the distal femur segment. The compressive properties of the ligament springs of the dummy were converted to the tensile properties of the bar elements such that the force-deflection response becomes equivalent. Other rigid components such as the distal femur and proximal tibia segments were modeled as rigid bodies. The knee joint model was validated in dynamic 4-point valgus bending against the experiment using the modified dummy knee joint by Bose et al. [10]. The bending moment at the knee joint as well as the tensile force for the Anterior Cruciate Ligament (ACL), Posterior Cruciate Ligament (PCL) and Medial Collateral Ligament (MCL) were compared between the FE simulation and experiment as shown in Figure 4, showing that the model accurately represents the bending response of the modified dummy knee joint.

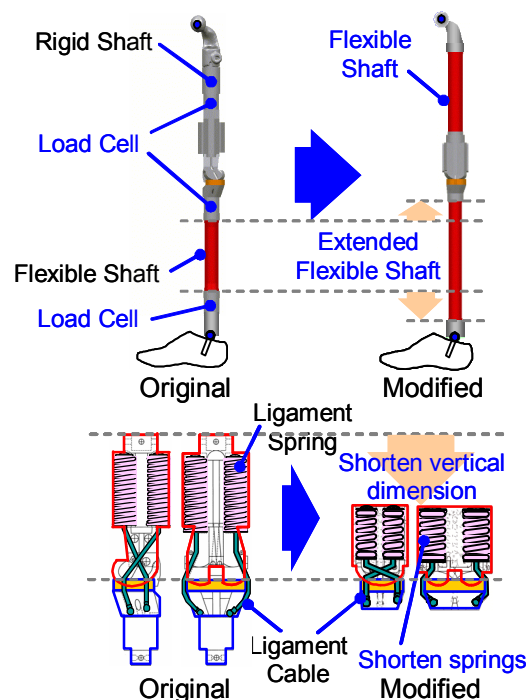


Figure 1. Modifications to lower limb of original POLAR II dummy

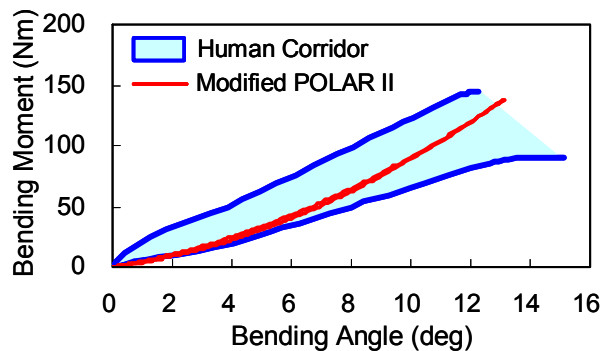


Figure 2. Comparison of knee moment-angle response

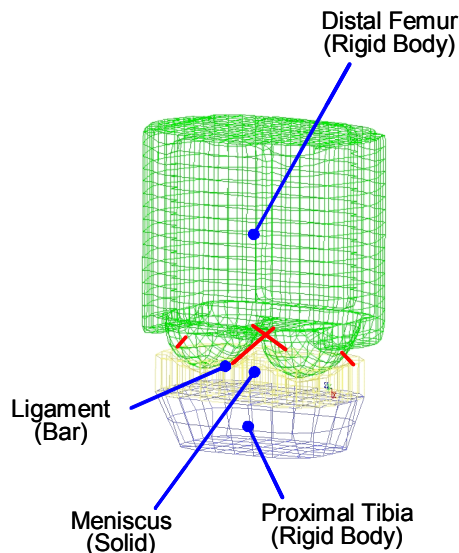


Figure 3. FE model for modified knee joint

FE HUMAN KNEE JOINT MODEL

A FE model for a human knee joint developed by Kikuchi et al. [11] was used in the current study for comparison purposes. Figure 5 shows a schematic for the FE human knee joint model. The geometry of the model was generated based on the MRI scans from a human volunteer. The ACL, PCL and Lateral Collateral Ligament (LCL) were modeled using solid elements to accurately represent the geometry of the ligaments. The MCL was modeled using shell elements considering its small thickness. A failure model using equivalent plastic strain thresholds was applied to the ligament models, and each ligament model was individually validated against published tensile tests up to failure at different loading rates using bone-ligament-bone specimens. The knee joint model was validated in dynamic 4-point bending against the same moment-angle response corridor as that used for the dummy knee response validation. The predicted MCL failure point was also validated against that for 50% probability of MCL failure obtained from the experiment based on which the response corridor was developed.

4-POINT BENDING SIMULATION

The FE dummy and human knee joint models were subjected to dynamic lateral bending in 4-point bending set-up. Since human response data are available only for valgus bending [9] and thus the biofidelity of the dummy knee joint was validated in valgus bending as well, it was decided to apply valgus bending to the dummy and human knee joint models. This comparison was considered to make sense because both the dummy and human knee joint models were validated in this knee bending configuration. Figures 6 and 7 illustrate model set-up for the human and dummy knee joint models, respectively. The 4-point bending set-up is similar to that used by Ivarsson et al. [9] for human knee joints. This set-up was also used by Takahashi et al. [8] and Bose et al. [10] for biofidelity evaluation of the original and modified POLAR II knee joints, respectively. An aluminum tube was attached to both sides of an isolated knee joint, and the pin joints on both sides provided a rotational degree of freedom about the y-axis. One of the two pin joints was allowed to translate in x-axis to provide simply supported boundary condition. A fork loaded the pipes on both sides to provide 4-point bending configuration at a loading rate of 1.0 degree/ms of the knee bending angle. The human knee joint model was loaded in valgus bending up to failure of the MCL, PCL and ACL. Figure 8 shows failure of these ligaments predicted by the human knee joint model in the 4-point bending simulation. As the knee joint was bent in valgus direction, the MCL failed first, followed by failure of the PCL and ACL.

INJURY MEASURES FOR DUMMY KNEE LIGAMENTS

Given that the moment-angle response of the modified dummy knee joint closely represents the average human response as shown in Figure 2, the knee bending angle at failure of each ligament was first determined from the bending simulation using the human knee joint model. Then the tensile force of each ligament of the dummy at corresponding knee bending angle was determined from the ligament tensile force versus knee bending angle plots obtained from the bending simulation using the dummy knee joint model. Figure 9 shows the time history of the knee bending angle from the human knee joint model. Failure of each ligament (MCL, PCL, ACL) was marked on the time history plot. With the human knee joint model, failure of the MCL, PCL and ACL occurred at the knee bending angles of 14.7, 22.0 and 29.1 degrees, respectively. Figure 10 shows the plots of tensile force versus knee bending angle for the MCL, PCL and ACL obtained from the dummy knee joint model. Tensile force at failure of each ligament marked on each plot was determined from the knee bending angle that corresponds to failure of each ligament predicted by the human knee joint model shown in Figure 9. The MCL generated highest force for a certain